Chapter 5
Formation of Thunderclouds

5.1 Cumulus Cloud

Almost everyone is familiar with cumulus clouds (Fig. 5.1a), which look like a piece of floating cotton, with a sharp outline and a flat bottom. When a growing cumulus resembles the head of a cauliflower, it is called a *cumulus congestus* (Fig. 5.1b). When conditions are just right, cumulus congestus continues to grow vertically, and the result is *cumulonimbus*, the thundercloud (Fig. 5.1c). It is a giant heat engine that converts the energy of the Sun into the mechanical energy of air currents and the electrical energy of lightning.

5.2 Formation of a Thundercloud

It all starts with the rays of the Sun shining on the face of the Earth. The sunlight warms the ground, and the ground warms the air in contact with it. The first requirement for the creation of a thundercloud is now satisfied. As the air in contact with the ground gets warmer, it expands and becomes lighter than the surrounding air. As a consequence, it starts rising. As we saw previously, the atmospheric pressure decreases with height, and this causes the rising air parcel to expand further. As it expands, it cools down. The second requirement for the creation of a thundercloud is that this rising air parcel should contain water or humidity. The ability of air to hold moisture in it decreases as the air temperature decreases. Consequently, as the rising air parcel cools, the moisture in the air starts condensing. It condenses into very small microscopic water drops, and millions of them are required to form a single rain drop. Visible clouds are made of these microscopic water droplets. Of course, these cloud droplets evaporate as the dry air surrounding a cloud mix with it. This happens mostly at the edges of the cloud and is the reason why clouds have a very sharp contour. Now, as we saw in Chap. 4, the air temperature decreases initially with increasing height.

V. Cooray, *An Introduction to Lightning*,
DOI 10.1007/978-94-017-8938-7_5

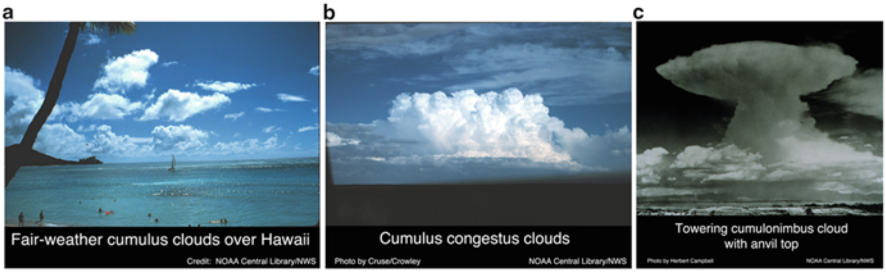

Fig. 5.1 Three stages of cumulus clouds: (**a**) cumulus, (**b**) cumulus congested, and (**c**) cumulonimbus (Photographs courtesy National Oceanic and Atmospheric Administration (NOAA), USA)

Under normal conditions the rate of decrease in temperature is approximately 6.5 °C for each 1,000 m of ascent. This rate of change in temperature is called the *environment lapse rate* [1]. Remember that our parcel of air expands as it rises, and its temperature decreases. If the air parcel does not contain saturated moisture and if we assume adiabatic conditions (i.e., no transfer of heat from air parcel to surroundings or vice versa), then its temperature drops by 10 °C per 1,000 m of its rise. Since this rate of decrease in temperature applies to an air parcel with unsaturated humidity, it is called the *dry adiabatic lapse rate* [1]. However, the atmospheric temperature does not drop so rapidly and very soon the air parcel becomes colder than the surrounding air, and this stops its upward journey (Fig. 5.2a). But if the rising air parcel contains moisture, heat is released as moisture condenses, and this heat warms up the rising air parcel. This heating due to condensation of water decreases the rate of drop in temperature of the air parcel to approximately 5.5 °C per 1,000 m. This is called the *wet adiabatic lapse rate*. Now, whether or not the conditions necessary for the creation of a thunderstorm exist depends on the wet adiabatic lapse rate. If the temperature in the atmosphere decreases faster than the wet adiabatic lapse rate, then the air parcel continues to rise in the atmosphere, i.e., it remains warmer than the surrounding air, and the final requirement necessary for the creation of a thundercloud is satisfied (Fig. 5.4b). Such an atmosphere is called an *unstable atmosphere*. The ability or potential of the atmosphere to generate thunderclouds is measured by a quantity called convective available potential energy, or CAPE. This parameter gives the measure of the potential energy available for a parcel of air as it moves upward in the atmosphere. It is calculated using the equation [2]

$$\text{CAPE} = \int_{Z_f}^{Z_e} g \frac{T_p(z) - T_e(z)}{T_e(z)} \, dz, \tag{5.1}$$

where g is the acceleration due to gravity, T_p is the temperature of the air parcel at height z, T_e is the temperature of the environment at height z, Z_f is the height of the atmosphere where the temperature of the environment starts to decrease faster than the moist adiabatic lapse rate of the atmosphere, and Z_e is the height of the

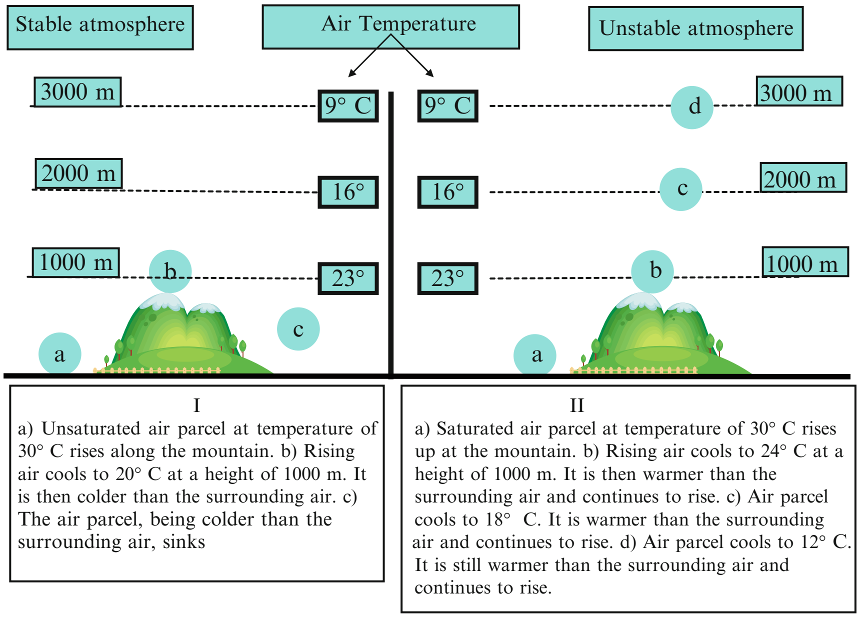

Fig. 5.2 The formation of thunderclouds depends on how fast the air temperature decreases with altitude and on the moisture content of the air at ground level. The atmosphere is unstable when rising air continues to be warmer than the surrounding air. This depends on the temperature of the surrounding air. The rising unsaturated air cools at a rate of 10 °C per 1,000 m. If the air is saturated, the moisture starts condensing as it cools, and the air parcel cools at a rate of 6 °C per 1,000 m. Therefore, the stability of the atmosphere depends on how the atmospheric temperature decreases with altitude and on the moisture content of the air at ground level. Note that in the diagram the environmental lapse rate is 7 °C/km, dry adiabatic lapse rate is 10 °C/km and the wet adiabatic lapse rate is 6 °C/km (Figure created by author)

atmosphere where the temperature of the air parcel becomes identical to that of the environment. The value of CAPE is measured in J kg^{-1} of air. In general, a value of CAPE greater than approximately 1,500 J kg^{-1} is considered to have a higher risk of thunderstorm formation. In summary, three conditions are necessary for the formation of a thundercloud: sunlight, moist air, and an unstable atmosphere.

A rising moist air column in the unstable atmosphere is the first stage of a thundercloud. This stage is called the *cumulus stage*. The air current pushes its way through the atmosphere at speeds as high as 50 m/s. This is the first stage of thundercloud formation (Fig. 5.3a). As the air rises higher and higher, its moisture condenses faster and faster. At the same time, the temperature of the air parcel continues to decrease. When the temperature of the parcel of air drops below 0 °C, the temperature at which water freezes, some of the tiny water droplets freeze and form tiny ice crystals. However, some of these tiny droplets remain as water even at temperatures lower than 0 °C. They are called *supercooled water droplets*. Some of these supercooled water droplets collide with tiny ice crystals and freeze directly on them. In this way, tiny ice crystals can grow in size. Such grown ice particles are called *graupel particles*. As the size of the graupel particles increases, they become heavier

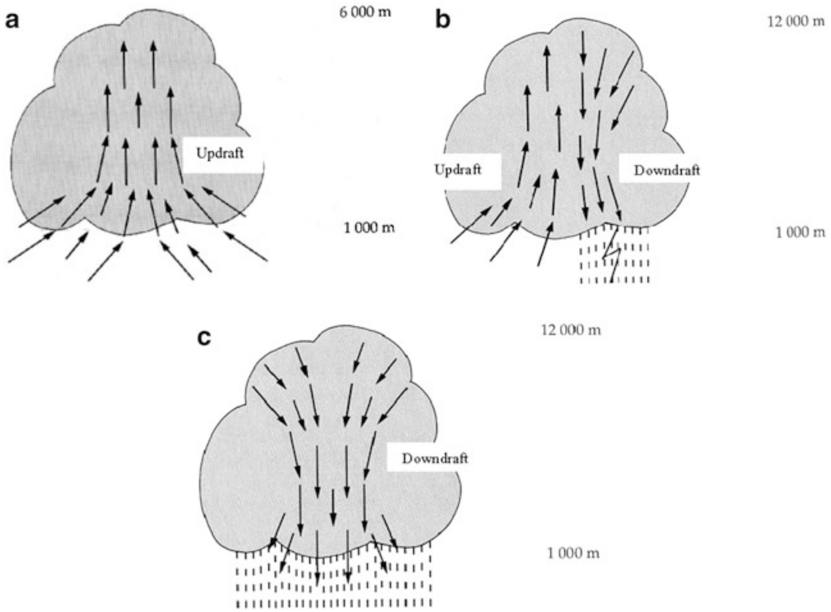

Fig. 5.3 (**a**) In the cumulus stage of the cloud, updrafts of warm humid air rise from the ground. Rapid updrafts prevent any precipitation from falling from the cloud. (**b**) As the cloud builds up to a height well above the level at which water freezes (i.e., freezing level), precipitation particles grow larger. At this stage, the cloud contains water droplets, supersaturated water drops, ice crystals, and graupel particles (soft hail). As the graupel particles become heavier, the rising air cannot keep them suspended and they begin to fall. As they fall, they drag the air with them, creating a downdraft. Updrafts continue to feed warm humid air into the cloud. Thunderstorms are very intense during the mature stage, and clouds produce lightning and heavy rain. (**c**) Falling precipitation causes downdrafts throughout the cloud, choking off the updrafts. With the cloud deprived of its rich supply of warm humid air, cloud droplets no longer form. The rain gradually becomes lighter and the downdrafts weaker. Finally, the cloud dissipates completely (Figure created by author)

and the rising air finds it difficult to push them upward against their weight; they start falling. This signals the mature stage of thundercloud formation. Now, what happens to the parcel of air? Will it go on rising forever? No. As discussed in Chap. 4, the temperature of the atmosphere decreases with height only initially and starts to increase once the tropopause is reached. The temperature inversion at the tropopause limits the growth of thunderclouds. Thus, the activity of thunderclouds is limited to the troposphere. In tropical regions, the tropopause is located approximately 15 km above the ground and in temperate regions approximately 10 km above.

As mentioned earlier, when graupel particles become heavier, the updraft is unable to sustain them, and they start falling. Some graupel particles are carried up and down in air currents for such a long time that they grow by the accretion of supercooled droplets and tiny ice crystals. Sometime they can grow up to a few centimetres in diameter and they are known as hail. The falling graupel particles collide with the tiny ice crystals and supercooled water droplets that are moving up in the updraft. As we will see in the next chapter, it is these collisions that researchers believe is the cause of electric charge generation inside a cloud [3].

When a cloud reaches this stage, it is called a *mature thundercloud* (Fig. 5.3b). It is usually at this stage that a cloud is capable of generating lightning flashes. The cloud top can extend to very large heights during this stage. This stage may last for approximately 15–30 min. At this time the amount of falling graupel particles also increases, and these falling particles start dragging down with them the surrounding air. This gives rise to a downward moving column of air and is called a *downdraft*. This downdraft opposes the movement of air in the updrafts. When the graupel particles reach warmer levels, they melt and give rise to water droplets, which fall to the ground as rain. With increasing precipitation the intensity of the downdrafts increases. This is the final stage of the cloud. In general, lightning activity takes place before strong downdrafts are established. This is why one intense lightning activity is usually observed before strong rain showers. The downdrafts bring cool air from higher altitudes to ground. This, combined with the rain, cools the air at ground level, which interrupts the formation of updrafts. The thundercloud has reached its death bed or the final stage (Fig. 5.3c). With the cessation of updrafts, the fuel necessary for the formation of the cloud is cut off. Deprived of its rich supply of warm humid air, the cloud stops growing. With time, even precipitation decreases. The rest of the cloud vaporizes into the atmosphere and disappears.

However, the preceding description relates to the activity of a single cell of a thundercloud. A thundercloud may have several cells, and when one cell dies down, another one may form. Therefore, lightning activity may continue for some time until all the energy available for updrafts are expended and the hot humid air is replaced by the cold air that comes down in the downdrafts. It is possible that one thundercloud may trigger the formation of another cloud. The cool air that comes down during the final stage of the thundercloud may spread outward and force the surrounding warmer air to rise, generating more thunderclouds. This process may last for hours until all the moist air and the heat are expended inside the thunderclouds.

Thunderstorms that are caused by direct heating of moist air at ground level by sun are called convective thunderstorms. Usually these thunderstorms occur in relatively still air without strong winds. There are cases in which the formation of thunderstorms is aided by the lifting of incoming air along the slopes of a mountain. Thunderstorms formed in this manner are called *orographic thunderstorms* (Fig. 5.4). In addition to such storms, there are others called *frontal thunderstorms*. These occur when large masses of cold air penetrate into a region with warm moist air. The cold incoming air wedges under the warm moist air and provides it with an upward thrust that is necessary for the formation of thunderstorms (Fig. 5.5). This rising warm air creates thunderstorms along the front of the incoming cold air mass. The same thing can happen when warm air flows into a region with cold air. The warm moist air slides up over the cold air mass, triggering thunderstorms. However, along a warm front the rise of warm air above the cold air is more gentle, and consequently the formation of thunderstorms is less probable than in the case of cold fronts. Cold fronts have a more severe boundary between the warm and cold air and are more likely to create thunderstorms.

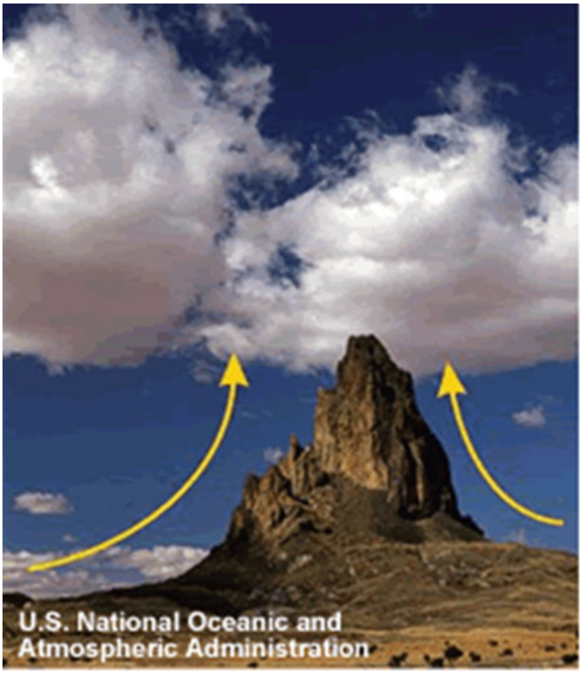

Fig. 5.4 Thunderstorms are formed when moist hot air is lifted up as it passes across a mountain. These types of thunderstorm are called *orographic thunderstorms* (Diagram courtesy National Oceanic and Atmospheric Administration (NOAA), USA)

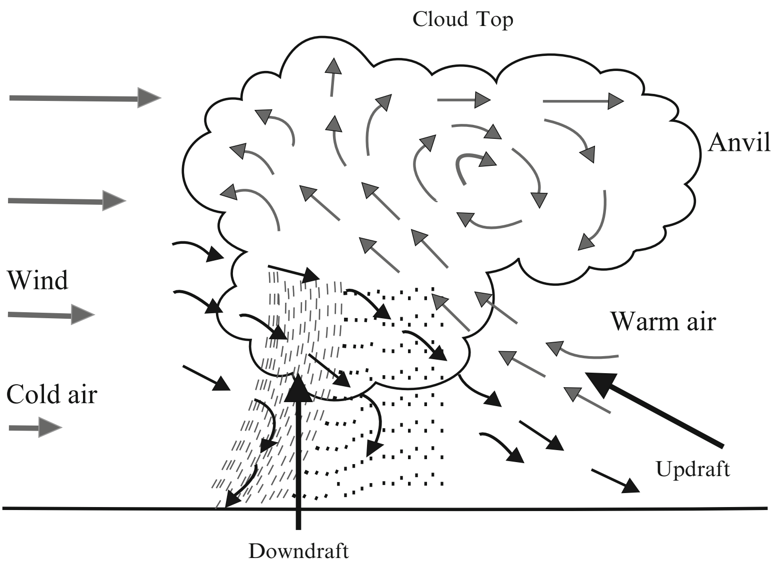

Fig. 5.5 Thunderstorms are formed when cold air masses enter a region with warm air. The cold air wedges under the warm air, resulting in an upward movement of warm air (Figure created by author based on information available in the literature)

A thundercloud is not the only natural element capable of generating lightning. Lightning can be generated in sandstorms, which usually occur in deserts. Lightning can also occur during the eruption of volcanoes. However, the charge generation mechanisms in sandstorms and volcanic plumes are not yet fully understood. Lightning is also produced around the fireballs of nuclear explosions. In this case, the enormous energy released by a nuclear bomb strips off electrons from atoms and in this way produces regions of positive and negative charges. The intense electric fields created by these charges give rise to lightning flashes.

References

1. Ahrens CD (2003) Meteorology today. Brooks/Cole-Thomson Learning, Pacific Grove, West Publishing Company, New York
2. Chandrasekar A (2010) Basics of atmospheric science. PHI Learning Private Limited, New Delhi
3. Jayaratne R (2003) Thundercloud charging mechanisms. In: Cooray V (ed) The lightning flash. IET Publishers, London